Gadolinium in Water: Zen and the Art

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גדוליניום

"Gadol" = Great!

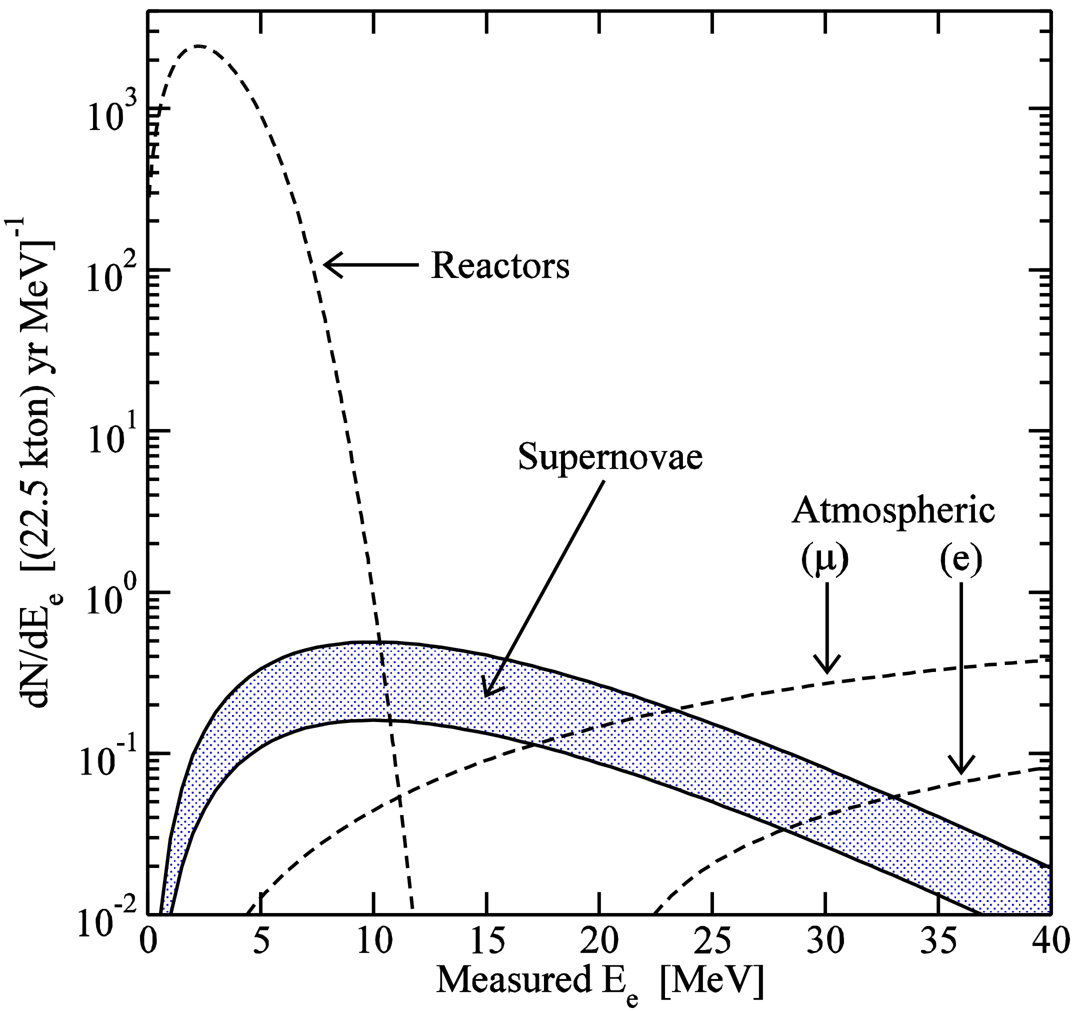
In 2003, John Beacom and I put out the original GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

It proposed loading big WC detectors, specifically Super-K, with water-soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

[hep-ex/0309300, Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Here's what the coincident signals in Super-K with 0.2% of $GdCl_3$ or $Gd_2(SO_4)_3$ will look like (energy resolution is applied):



$\bar{\nu}_e + p \rightarrow e^+ + n$

spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

$\lambda = \sim 4$ cm, $\tau = \sim 30\ \mu s$

→ A few SN events/yr in Super-K with Gd

In addition to our two guaranteed new signals, SN and reactor, adding gadolinium to SK will provide a variety of other interesting possibilities:

- Sensitivity to very late-time black hole formation
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- (Free) proton decay background reduction (5X)
- New long-baseline flux normalization for T2K
- Matter- vs. antimatter-enhanced atmospheric ν samples

All of this could work even better in an much larger detector.

Indeed, such a massive new project will *need* to have some new physics topics to study!

To make GADZOOKS! work, we will have to:

Dissolve the gadolinium sulfate in the water

→ Easy and fast (pH control)

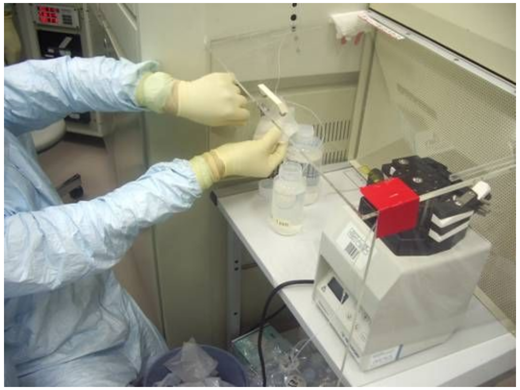
Remove the gadolinium efficiently and completely when desired

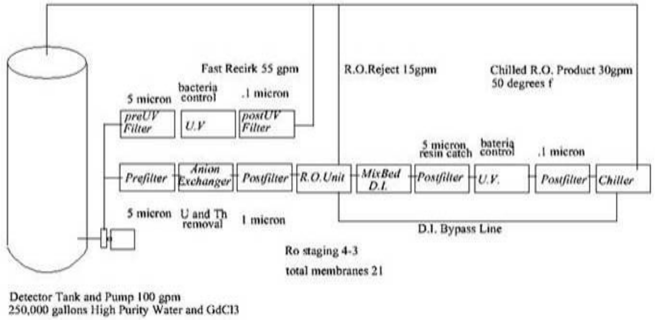
→ Also easy and fast (pH control)

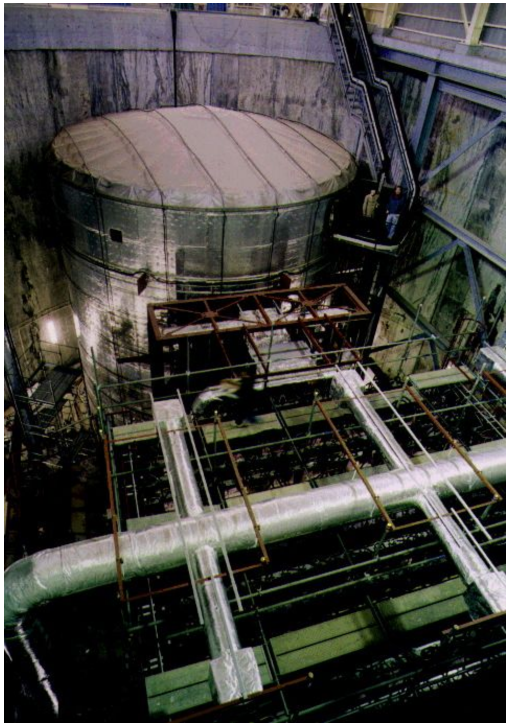
Keep pure water pure yet retain gadolinium in solution

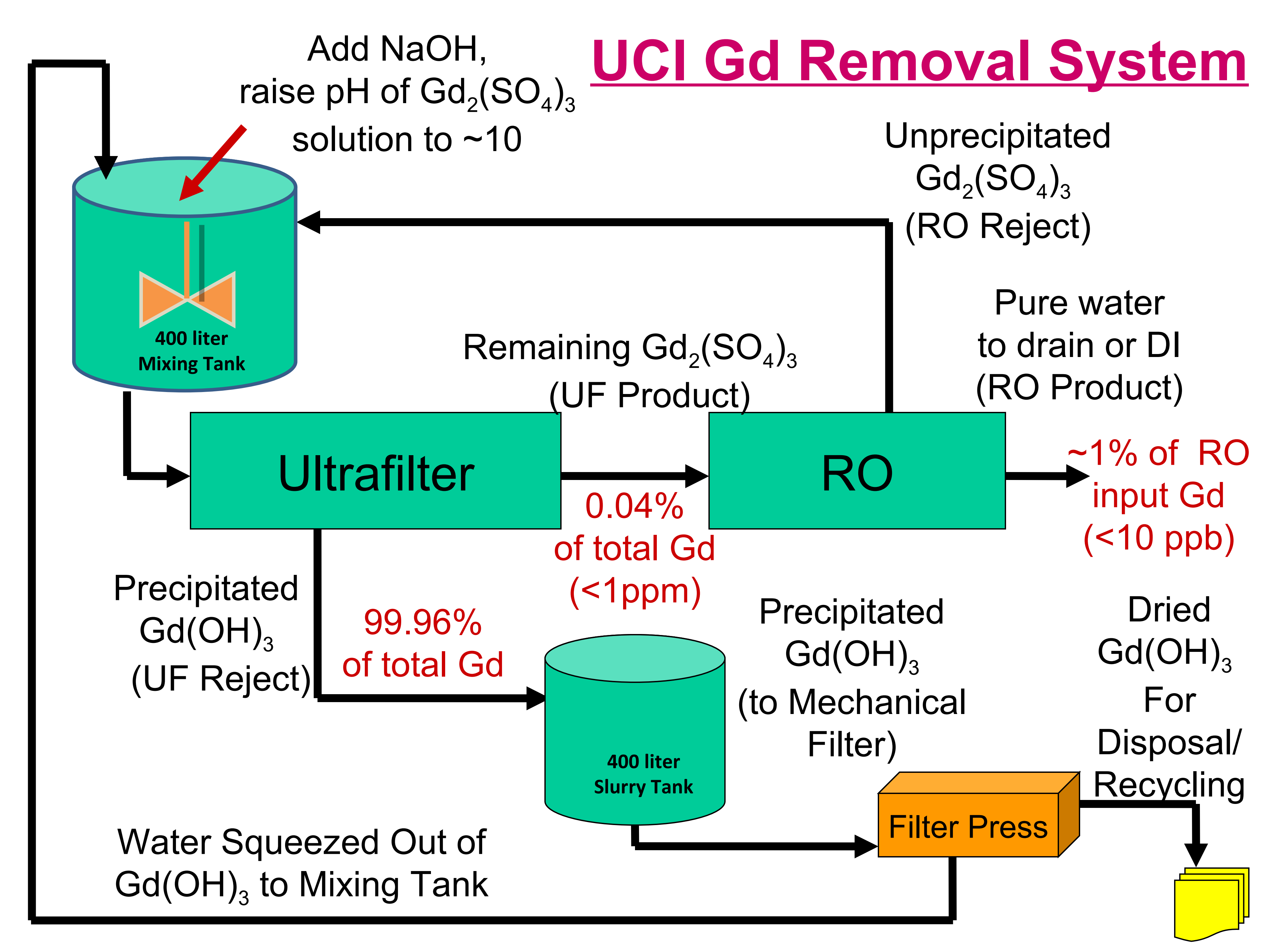
→ The tricky part; need a selective Gd filtration system

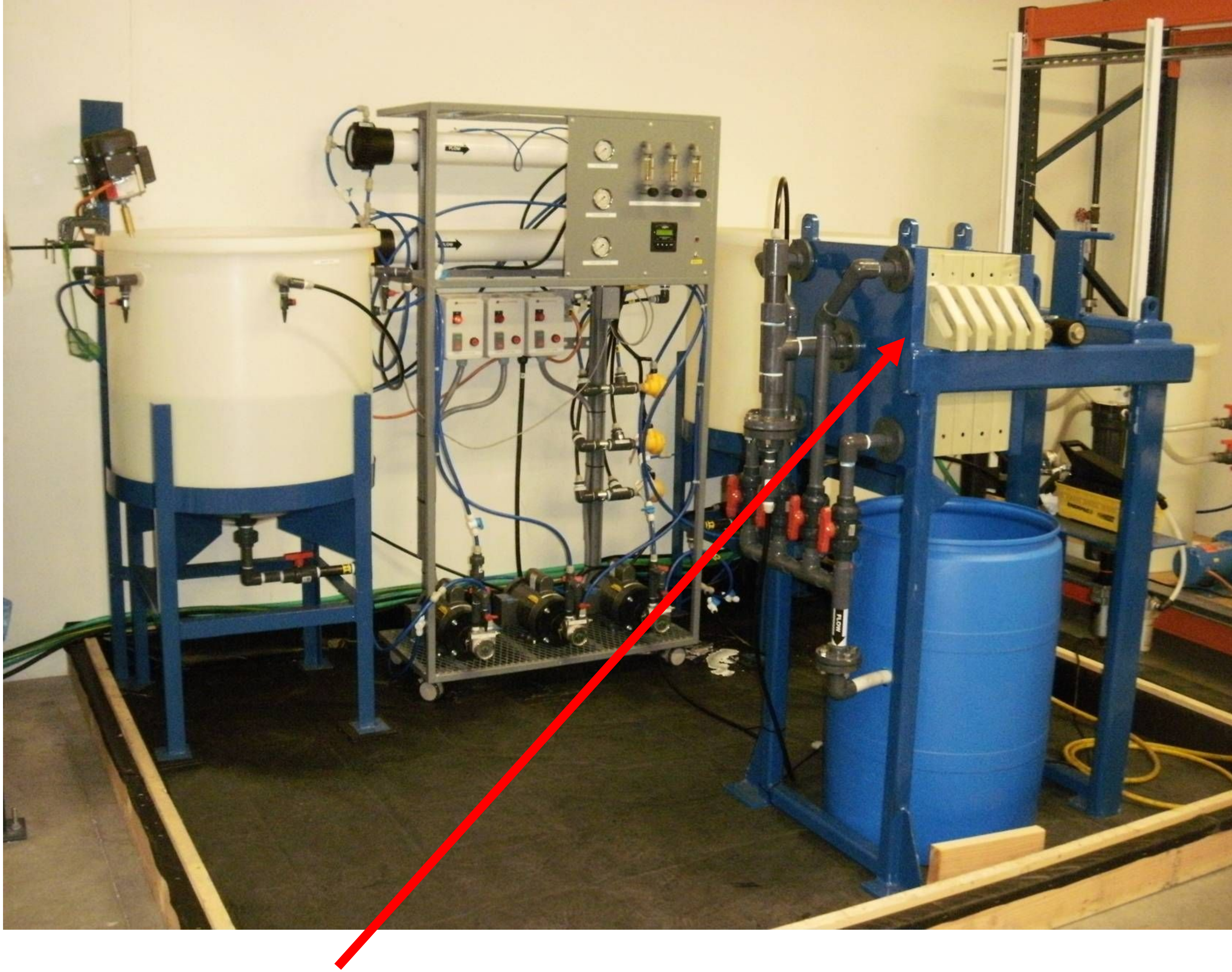
Over the last eight years there have been a large number of Gd-related R&D studies carried out in the US and Japan:





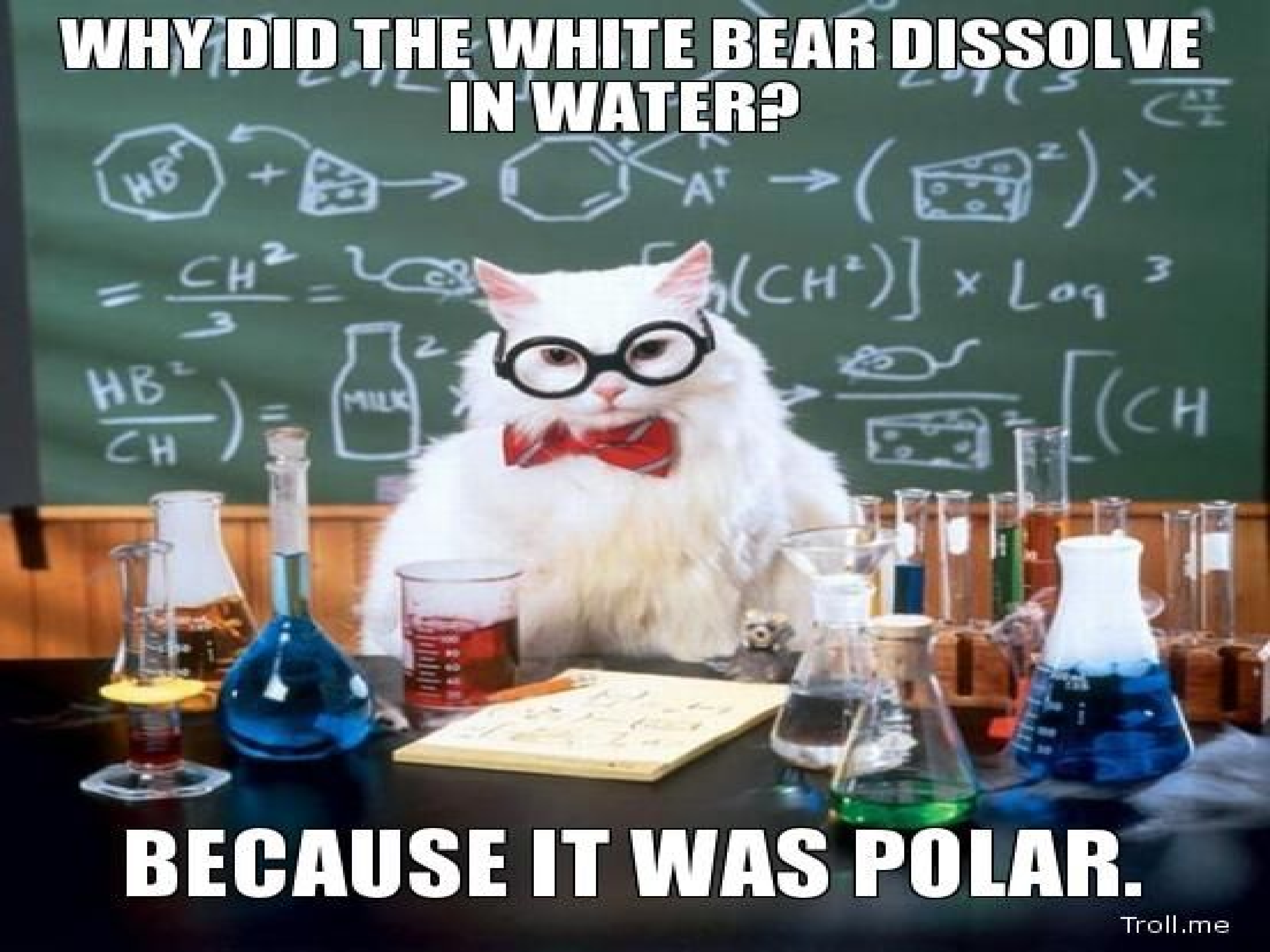


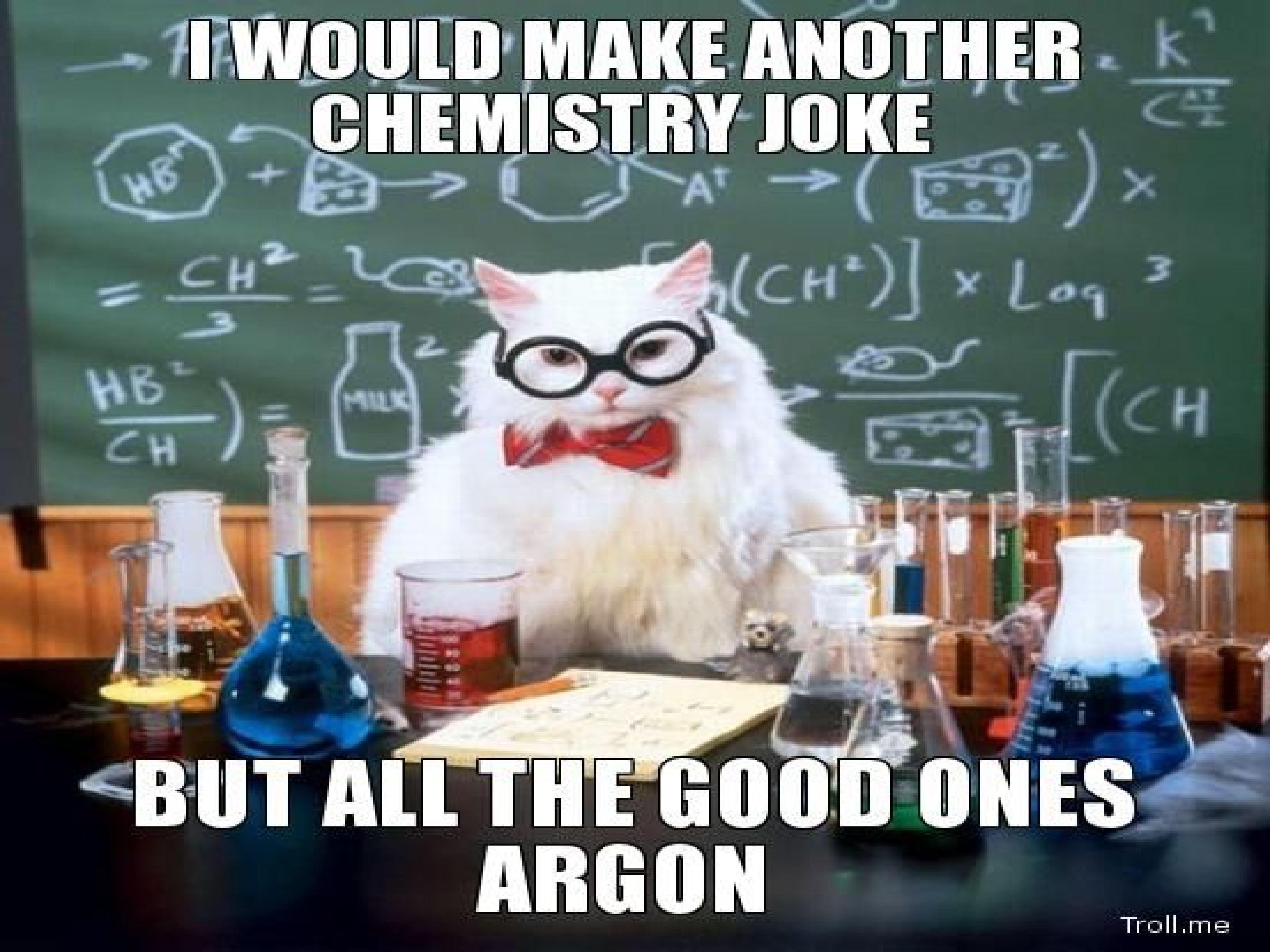

UCI Gd Removal System
Add NaOH, raise pH of $Gd_2(SO_4)_3$ solution to ~10
400 liter Mixing Tank
Unprecipitated $Gd_2(SO_4)_3$ (RO Reject)
Pure water to drain or DI (RO Product)
Remaining $Gd_2(SO_4)_3$ (UF Product)
Ultrafilter
RO
0.04% of total Gd (<1ppm)
~1% of RO input Gd (<10 ppb)
Precipitated $Gd(OH)_3$ (UF Reject)
99.96% of total Gd
400 liter Slurry Tank
Precipitated $Gd(OH)_3$ (to Mechanical Filter)
Dried $Gd(OH)_3$ For Disposal/ Recycling
Filter Press
Water Squeezed Out of $Gd(OH)_3$ to Mixing Tank



Gd Filter Press Removal System; January 5th, 2011

Adding 383 grams $Gd_2(SO_4)_3$ to 191 liters of H_2O; January 5th, 2011

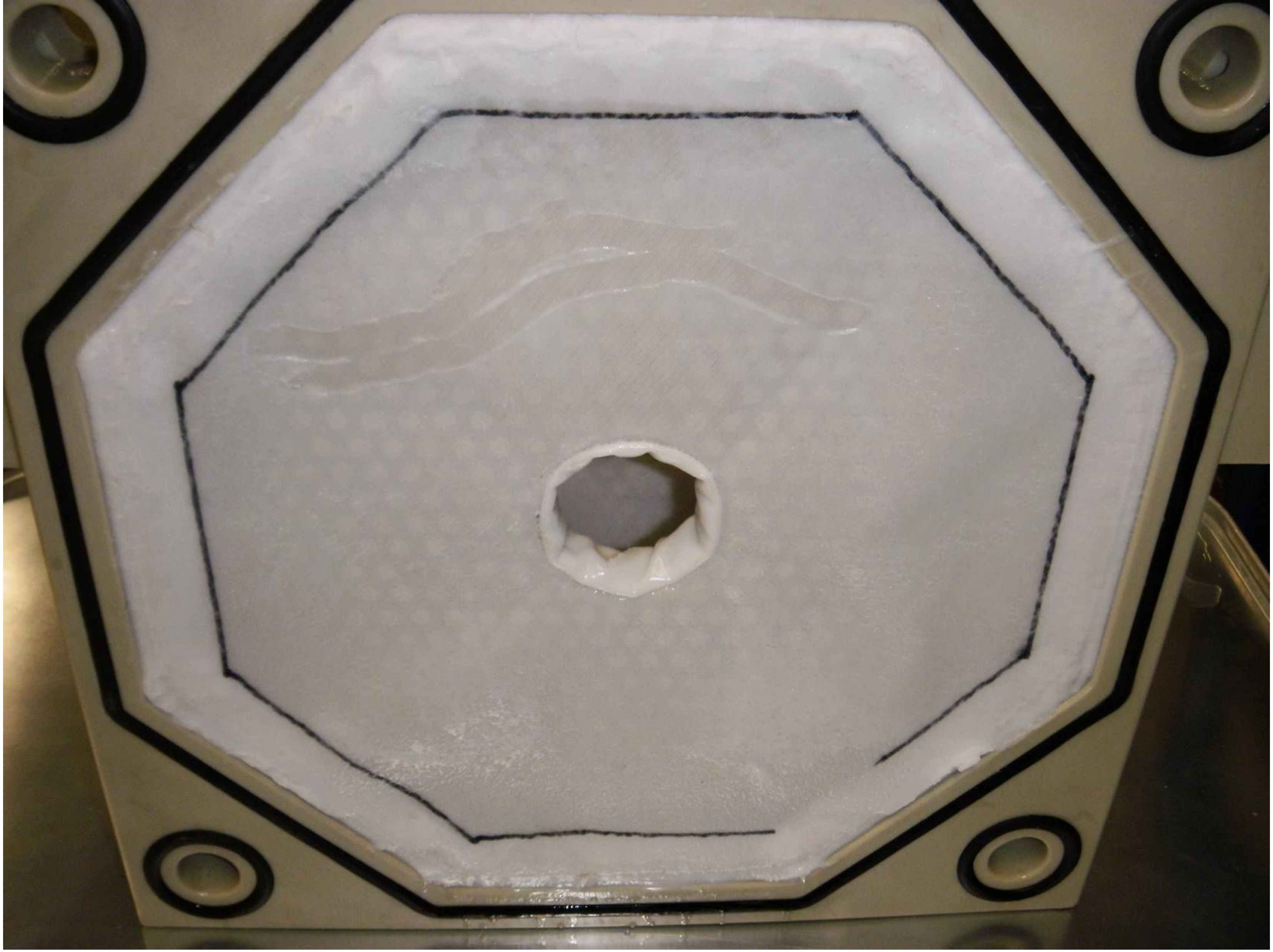

WHY DID THE WHITE BEAR DISSOLVE IN WATER?
BECAUSE IT WAS POLAR.
Troll.me


I WOULD MAKE ANOTHER
CHEMISTRY JOKE
BUT ALL THE GOOD ONES
ARGON
Troll.me

Resulting solution is rather cloudy; January 5th, 2011

After treating with H_2SO_4, solution is completely clear; January 5th, 2011

Precipitate forms after raising pH to 10 with NaOH; January 5th, 2011
This is concentrated by ultrafiltration and forced through a filter press.

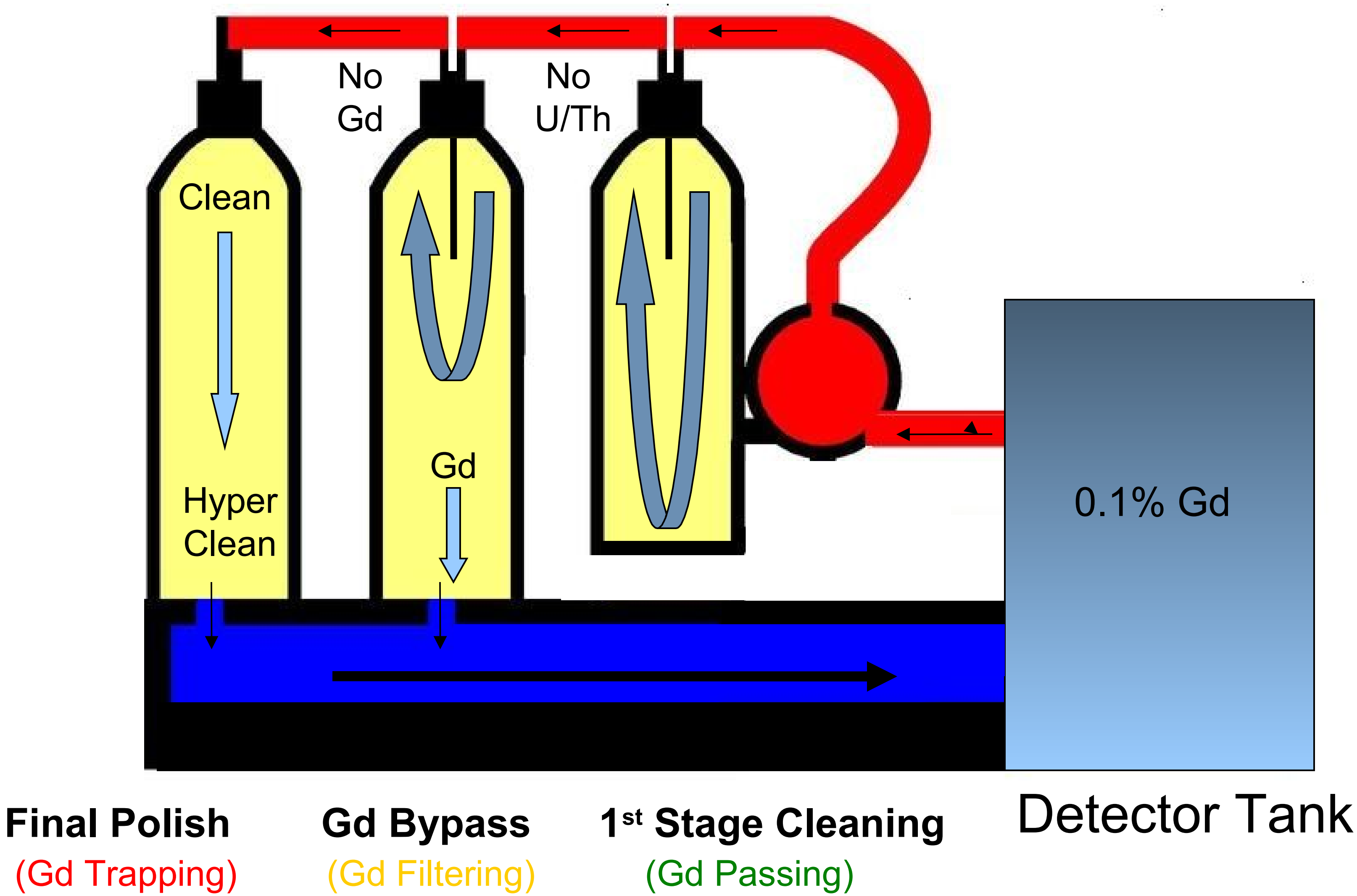


Wet $Gd(OH)_3$ after passing through filter press; January 6th, 2011

One day later, $Gd(OH)_3$ is dry and has crystallized; January 7th, 2011

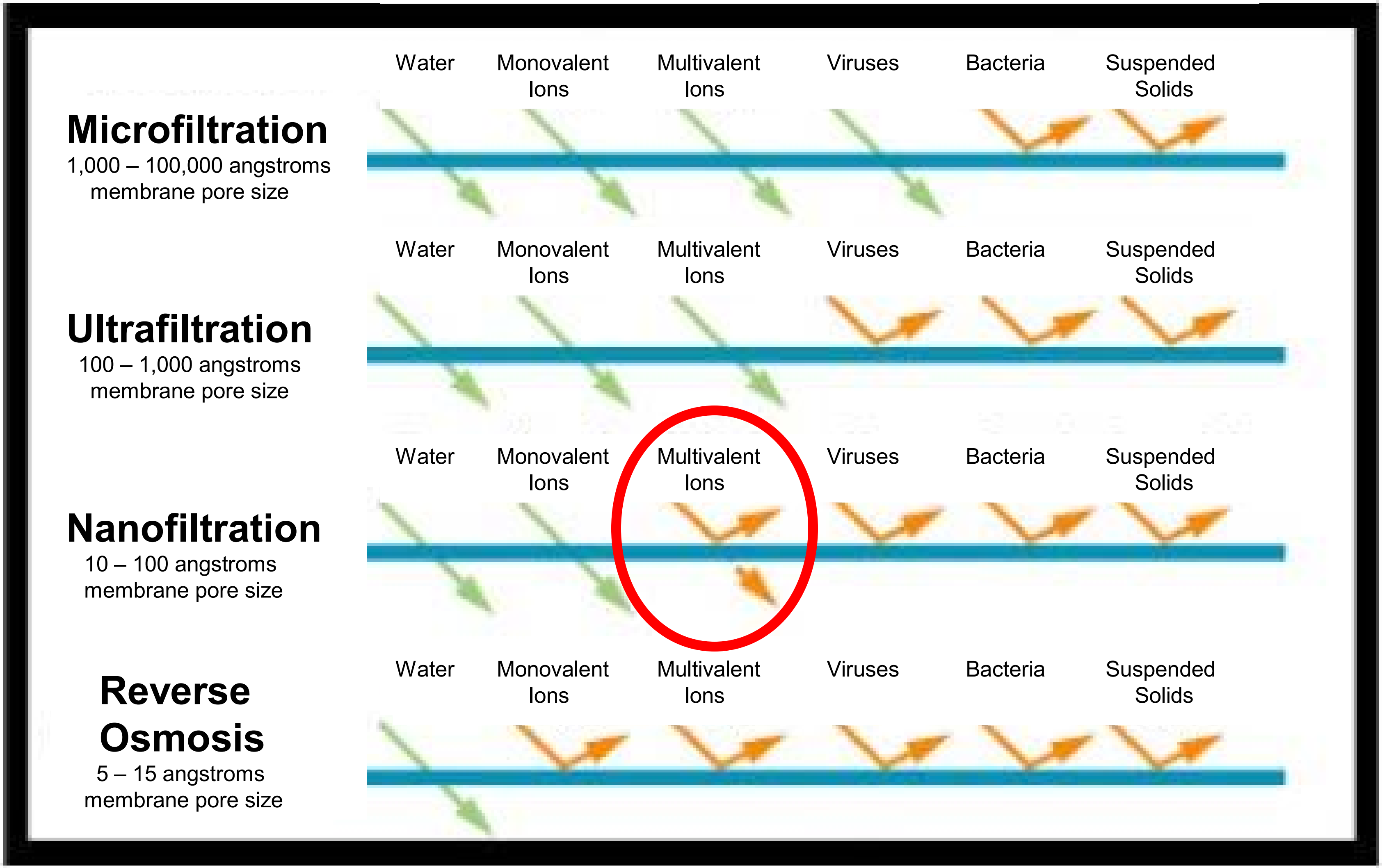
The resulting dried $Gd(OH)_3$ precipitate; January 2011.

In highly schematic form, we would like a water system with selective Gd filtering to work something like this:

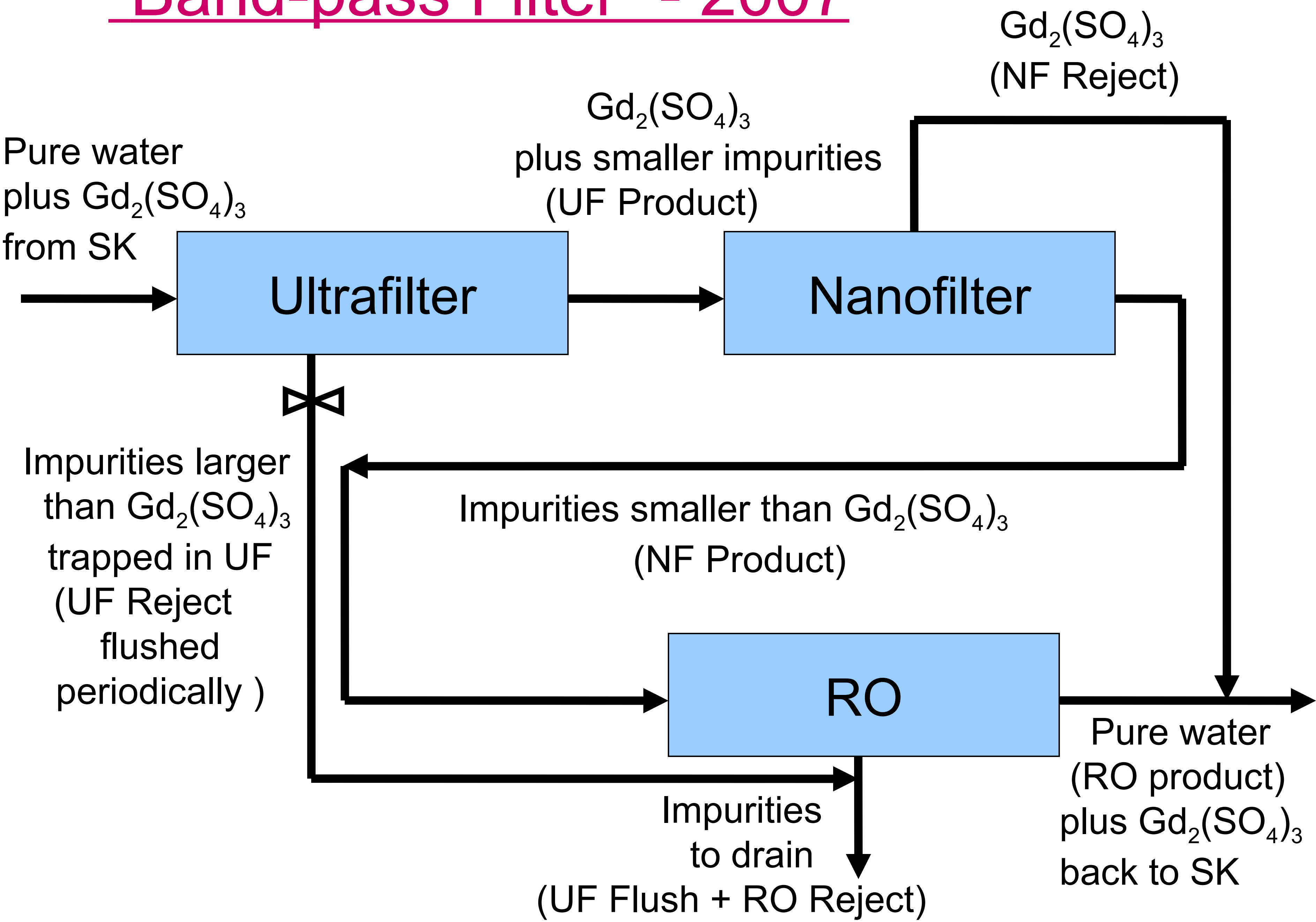


Membrane-based Filtering Technologies

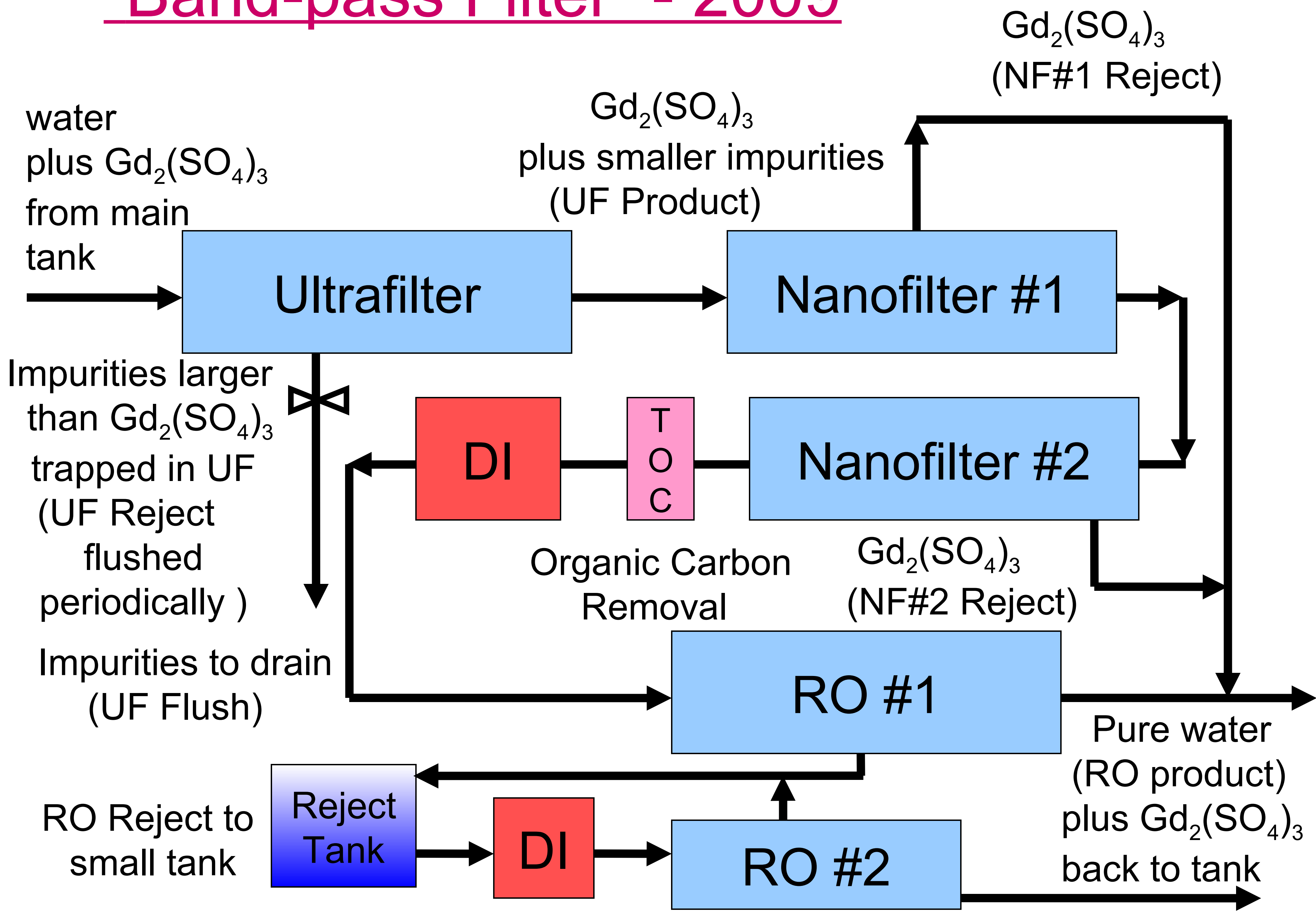
$$Gd_2(SO_4)_3 \rightarrow 2\ Gd^{3+} + 3\ (SO_4)^{2-}$$



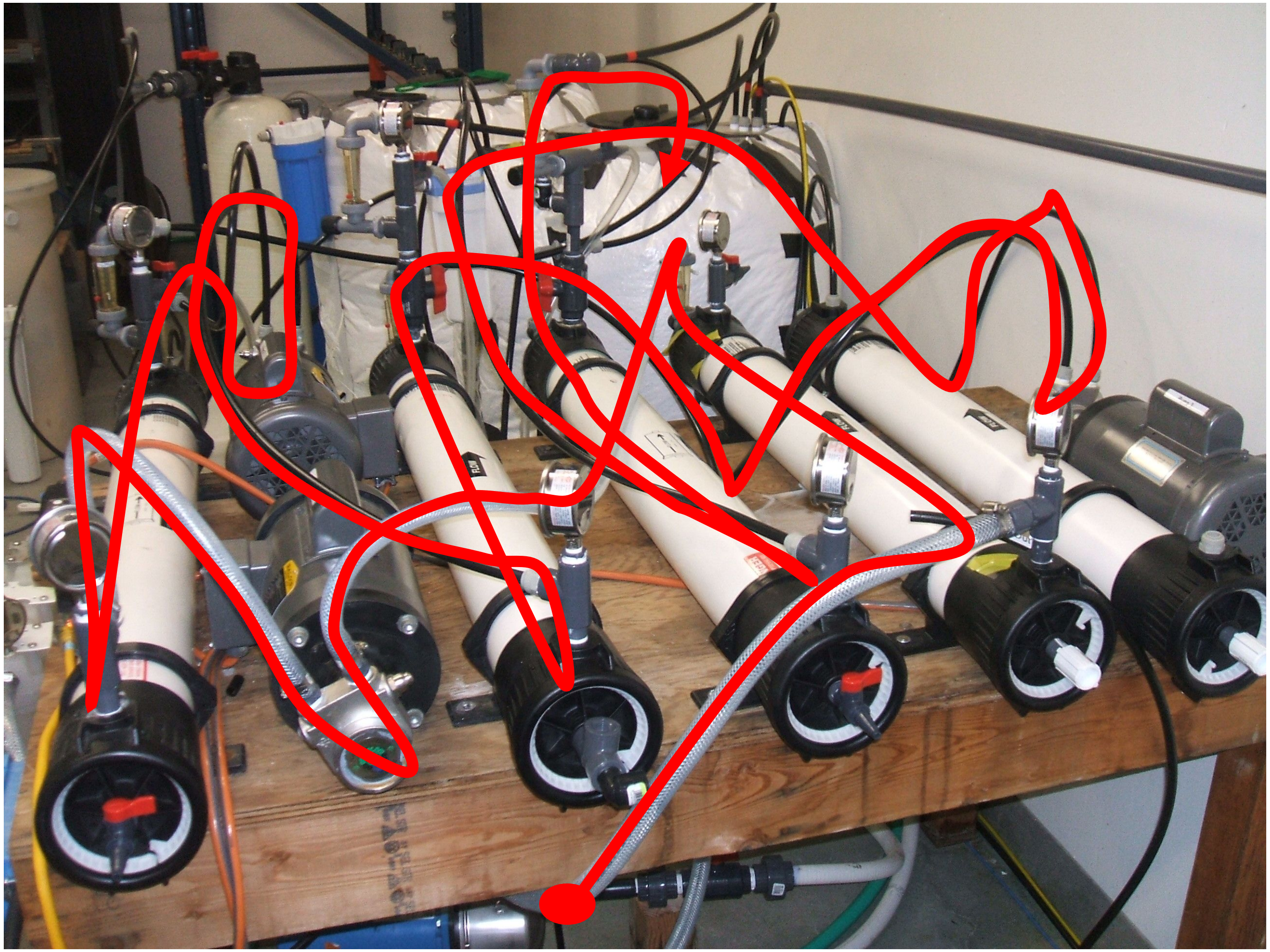
“Band-pass Filter” - 2007



“Band-pass Filter” - 2009



Prototype Selective Filtration Setup @ UCI

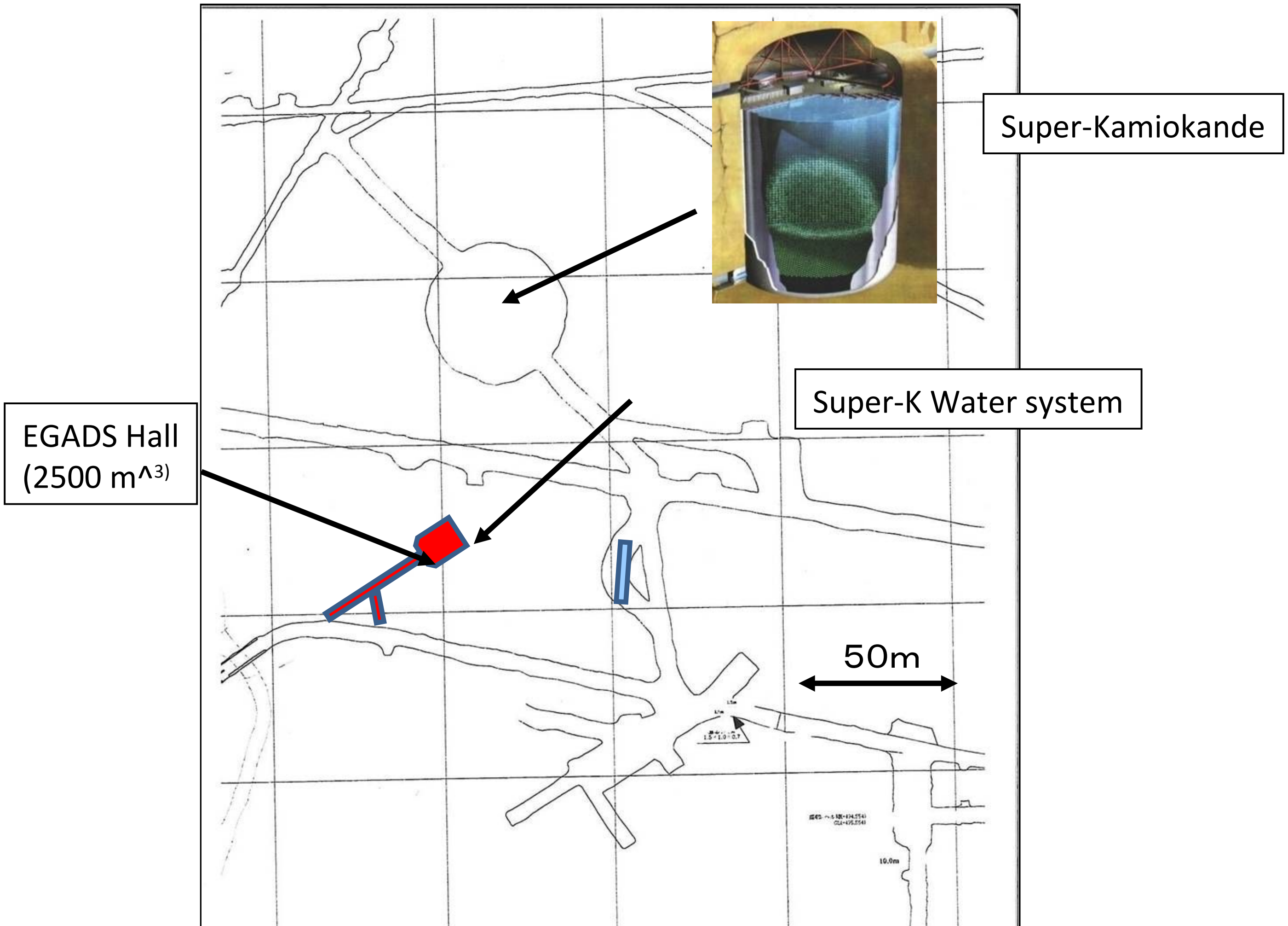


Membrane Pre-Flush

Nanofilter #1 Nanofilter #2 Reverse Osmosis Ultrafilter

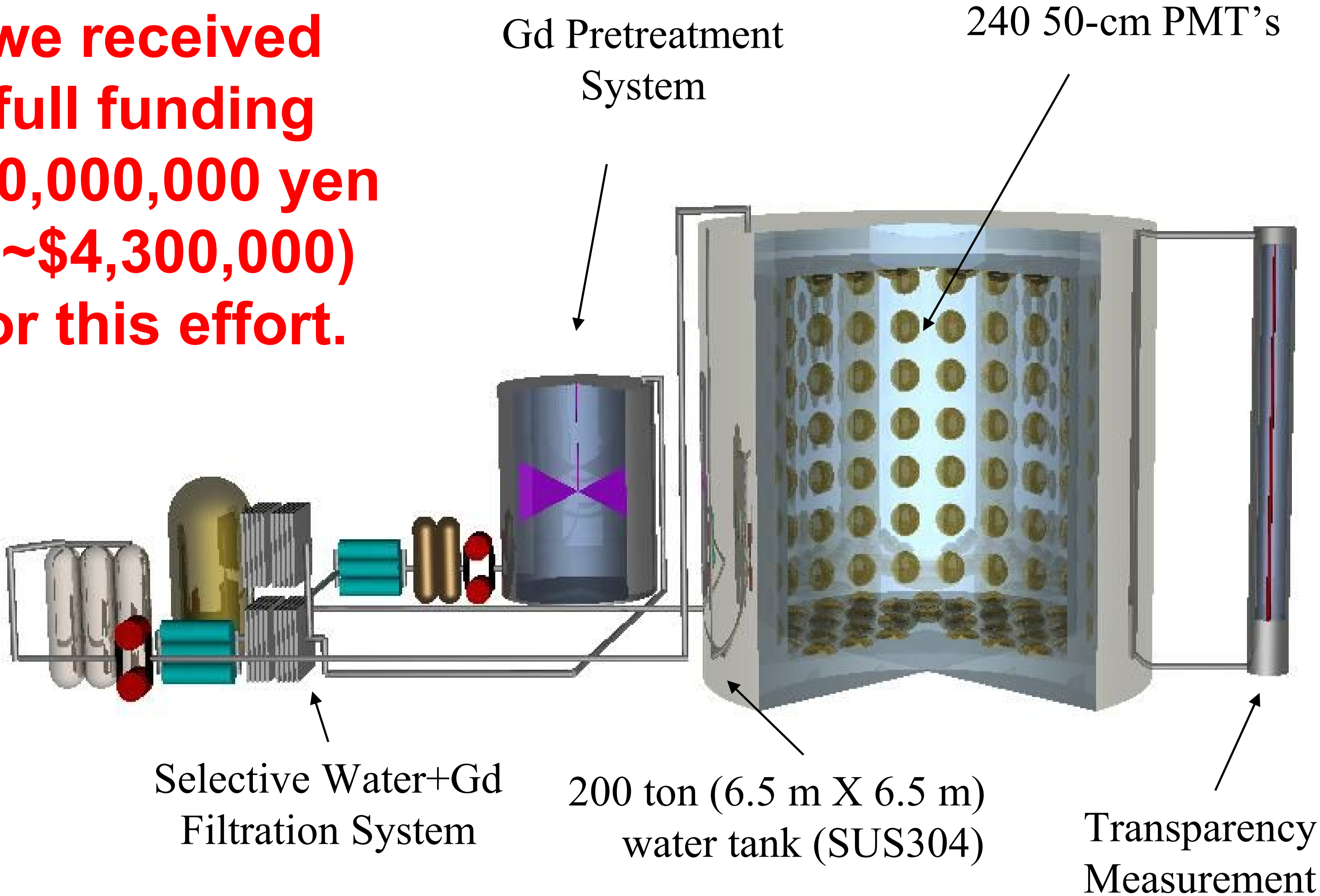
We've built a new, dedicated Gd test facility, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

This 200 ton-scale R&D project is called EGADS – Evaluating Gadolinium's Action on Detector Systems.



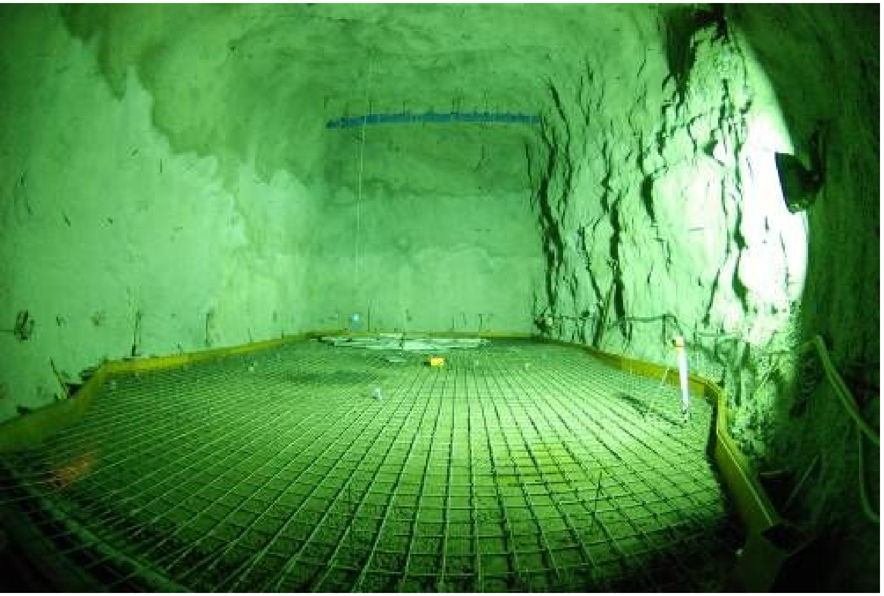
EGADS Facility

In June of 2009 we received full funding (390,000,000 yen = ~$4,300,000) for this effort.



Hall E and EGADS

12/2009



2/2010

6/2010

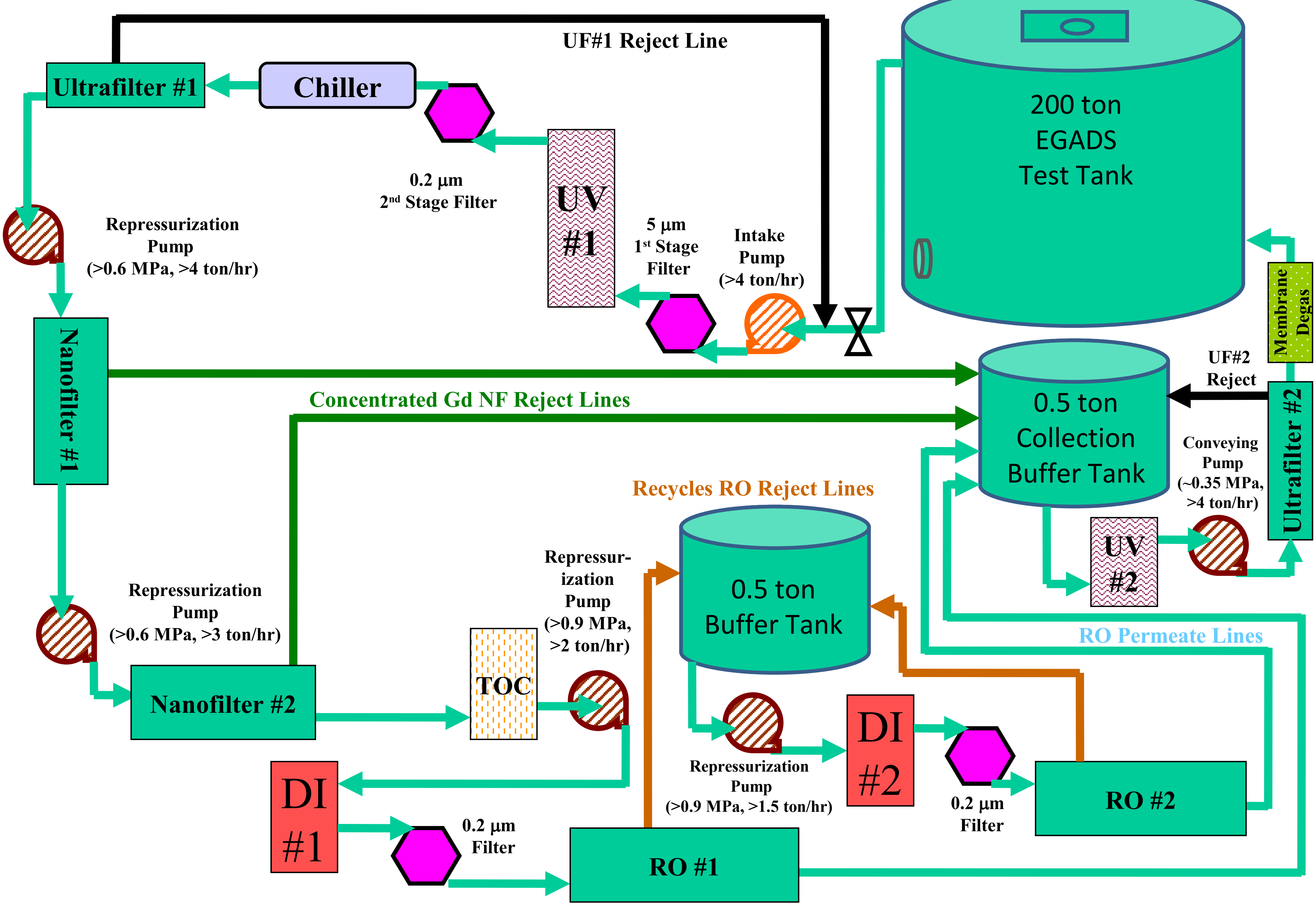
12/2010

5/2011

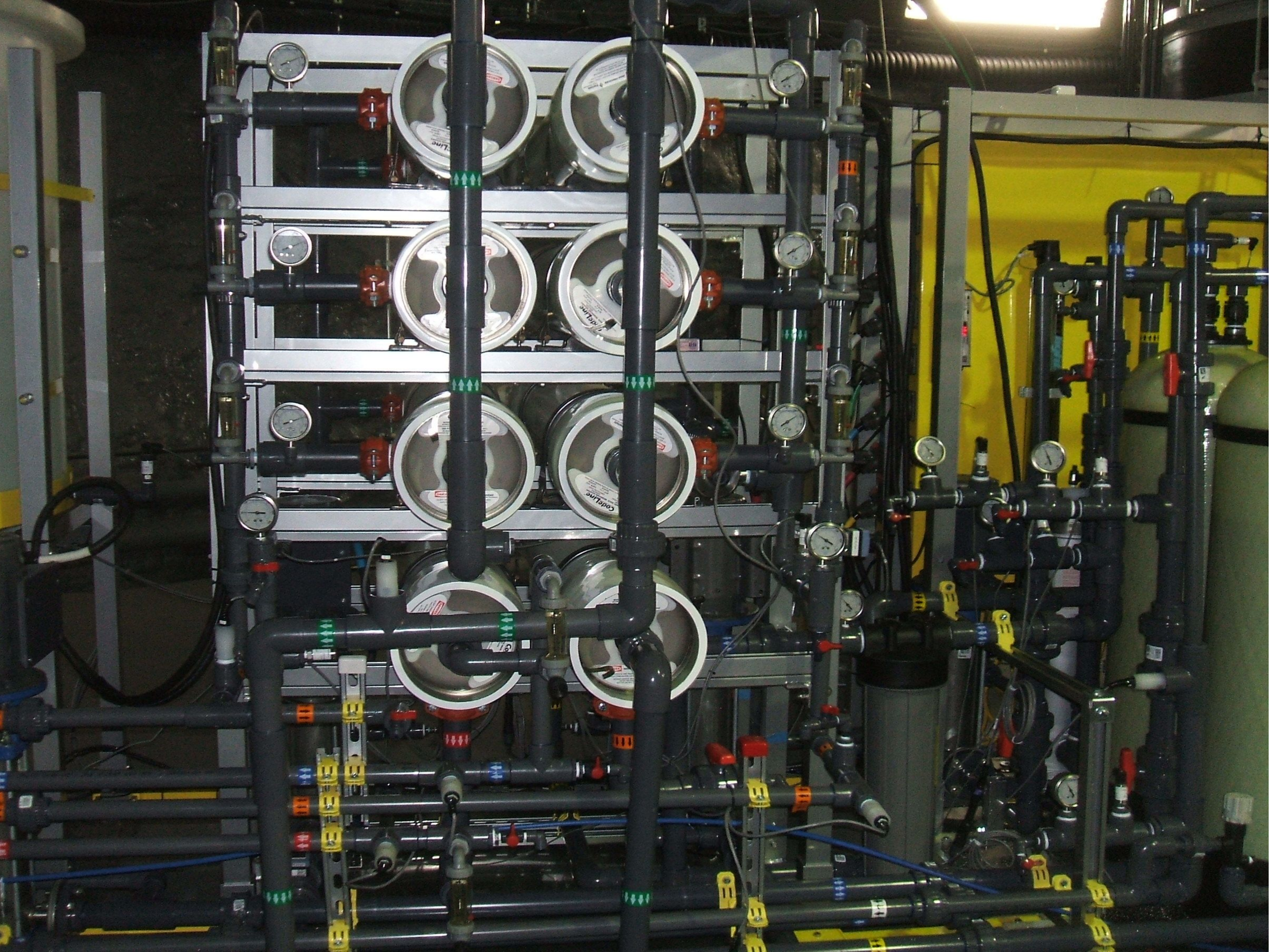
2/2011

Hall E and EGADS

EGADS "Band-Pass" Filter - 2011



Selective filtration system in Hall E; early 2011.

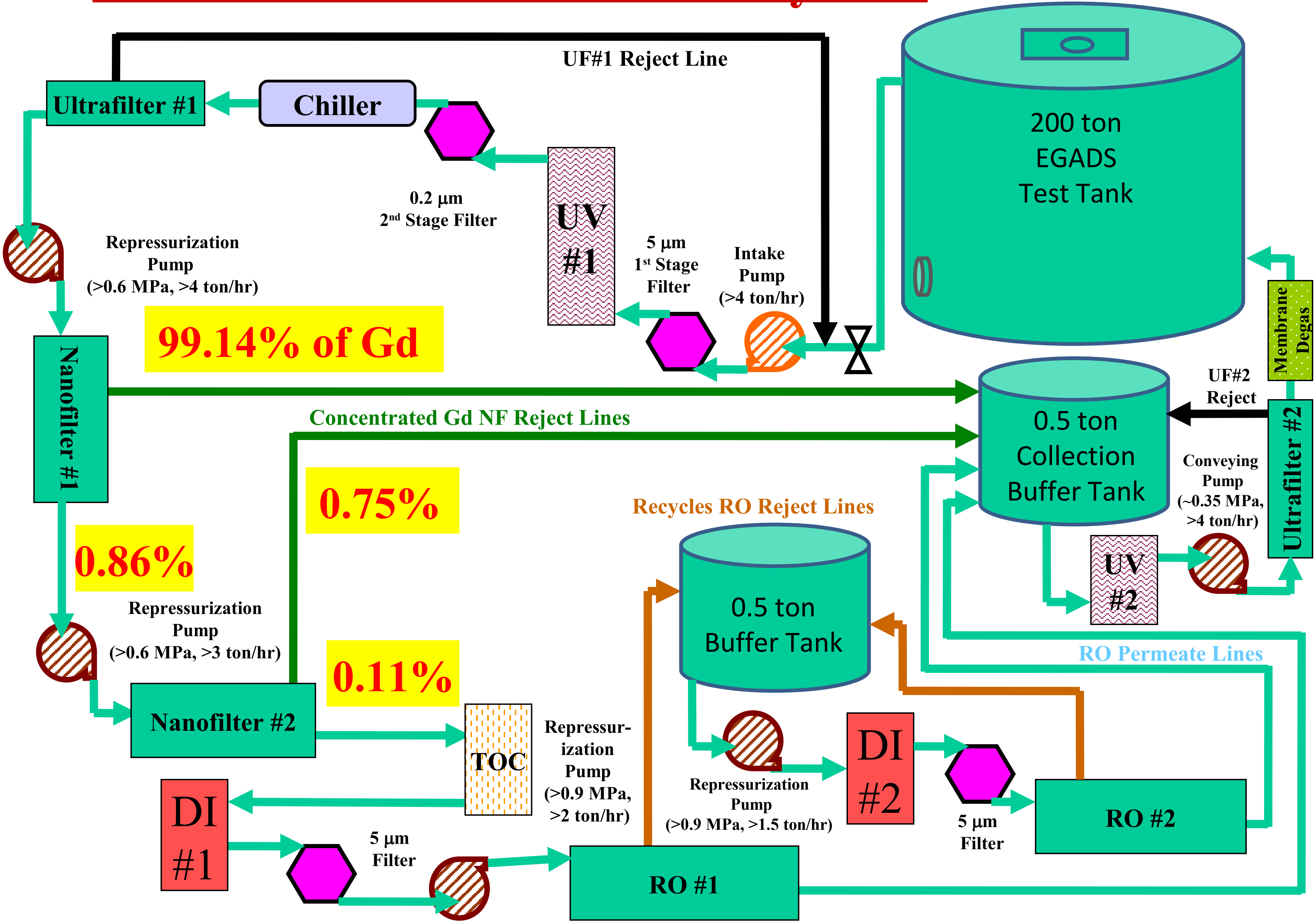


Dumping first batch, 28 kg, of $Gd_2(SO_4)_3$ into 15-ton pre-treatment tank on August 1st, 2011.

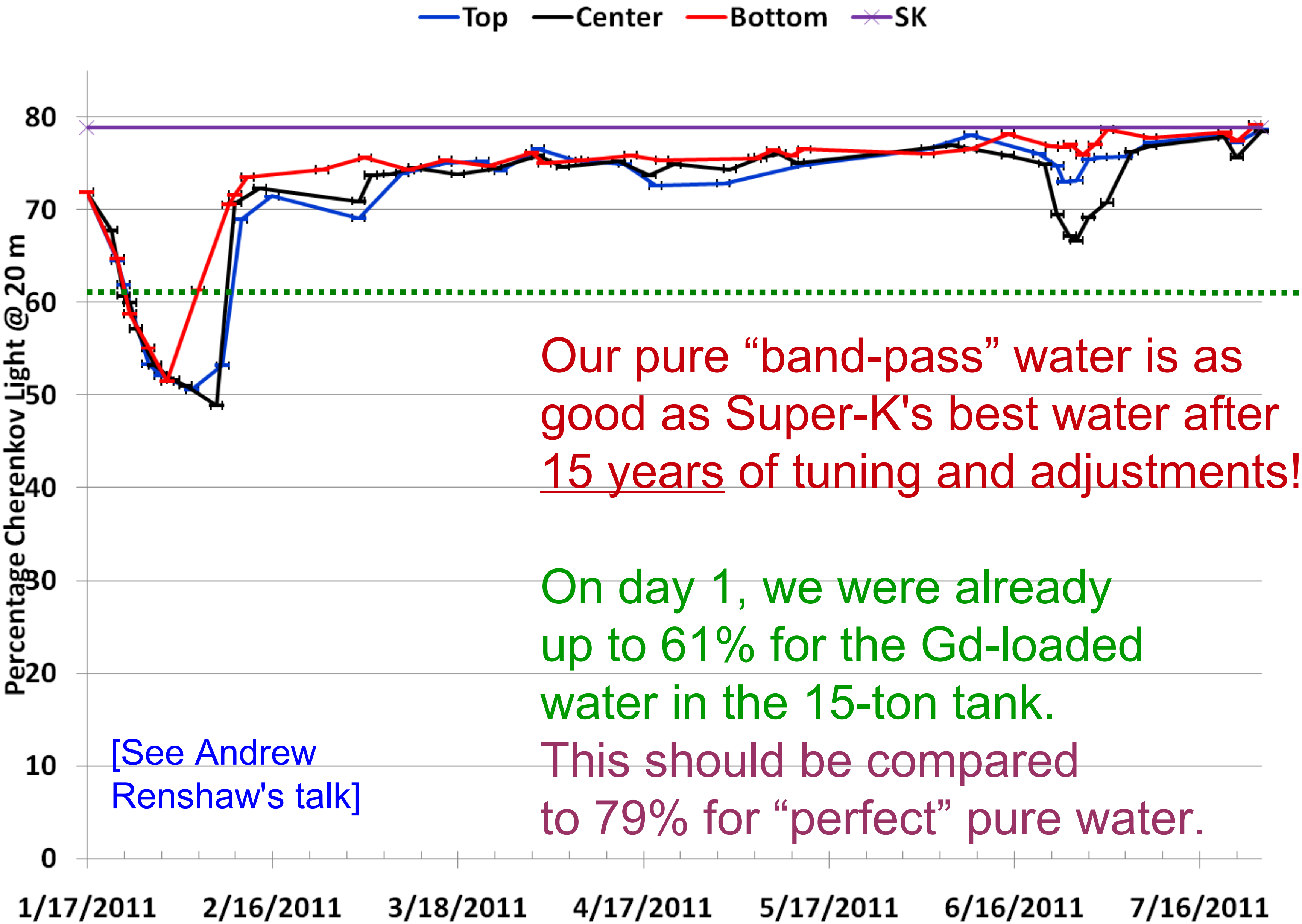
After recirculating through the pre-treatment system's 3 micron and 0.2 micron filters @ 1.5 tons/hr overnight, we put the Gd water into the main EGADS system at 17:48 on August 2nd.

EGADS Selective Filtration System

Oct. 2011



Cherenkov Light Remaining at 20 m (200-ton tank)



Our pure "band-pass" water is as good as Super-K's best water after 15 years of tuning and adjustments!

On day 1, we were already up to 61% for the Gd-loaded water in the 15-ton tank.

This should be compared to 79% for "perfect" pure water.

[See Andrew Renshaw's talk]

EGADS Schedule

2009-10: Excavation of new underground experimental hall, construction of stainless steel test tank and PMT-supporting structure (all completed, June 2010)

2010-11: Assembly of main water filtration system (completed), tube prep (completed), mounting of PMT's, installation of electronics and DAQ computers

2011-13: Experimental program, long-term stability assessment

At the same time, material aging studies will be carried out in Japan, and transparency and water filtration studies will continue in the US

The goal is to be able to state conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective.

Target date for decision = 2012

Four weeks ago, the official [Hyper-Kamiokande] Letter of Intent appeared on the arXiv:1109.3262

1.0 Mton total water volume
0.54 Mton fiducial volume

Gadolinium loading is part of the executive summary.